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ScienceDirect
Physics Procedia 56 (2014) 811 – 817
Physics Procedia

8th International Conference on Photonic Technologies LANE 2014

# Investigating thermal interactions in the case of laser assisted joining of PMMA plastic and steel

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**Abstract**

Laser transmission joining of dissimilar materials is a novel and promising area of researches on joining technology. However, processes during laser assisted metal plastic (LAMP) joining are not completely explained yet. In the course of this study, the authors investigated the joining process of PMMA plastic and steel by means of laser, as a part of their research on dissimilar material joining. The characteristic process temperature was measured during the joining by different heating conditions, to describe thermal interactions between the polymer and the metal part, and to better understand the mechanism of joining.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
*Keywords:* PMMA; steel; laser; joining; temperature analysis

## 1. Introduction

Lately, the spreading application of plastic materials and laser beam sources can be observed in the industry. This phenomenon is induced by the beneficial properties of polymers and laser technology: plastics have low density, are easily formable by moulding and are relatively cheap (Farazila et al., 2012, Holtkamp et al., 2010). Plastics are increasingly used as structural materials as well, where high strength bonding plays an important role (Grujicic et al., 2008). Laser processes are flexible, fast and can be automatised very well, the heat input is localised and low, which can be advantageous in case of laser assisted plastic material processing. (Fortunato et al. 2010). Lasers are already used to weld plastics in a transparent-absorbent way, however, research in the last years showed, that

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Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.089

transparent absorbent joining can be used to join plastics and metals as well. (Katayama et al., 2008, Bauernhuber et al., 2012). In this case, laser joining is able to solve the problems of typical polymer-metal joining technologies, like screwing, riveting and adhesives, due its characteristics listed above (Farazila et al., 2012) Nevertheless, since laser assisted metal-plastic (LAMP) joining is a young technology, it is necessary to clarify the processes present in the polymer material and on the metal-polymer interface during joining. To produce a good joint quality, it is indispensable to understand the heating process and know the temperature values during joining.

In this research, the author's aim was to characterize the thermal processes present during laser heating and joining of structural steel and poly(methyl methacrylate) (PMMA) plastic. The temperature was measured in the case of three different laser settings, and the effect of the usage of plastic in the heating process of steel pin was examined by thermocouple and thermovision systems.

## 2. Experiments

The materials used were a S235 structural steel in a pin geometry and a poly(methyl methacrylate) (Acriplex PMMA-XT) sheet. The thickness of the sheet was 2 mm, its size 15x15mm. The geometry of the steel pin sample and the experimental setup can be seen in Figure 1. The laser beam source was a LASAG SLS 200 type, pulse mode Nd:YAG laser with a maximal pulse power of $P_{max}=5.5\ kW$ and with an average power of $P_a=220\ W$. The power distribution of the laser beam was Gaussian ($TEM_{0,0}$). The temperature was measured with a K-type thermocouple, which was welded on the lateral surface of the steel pin, next to the face surface. The diameter of the thermocouple wire was 0.25 mm. The temperature distribution of the surface and the heating process was detected by thermovision camera (type FLIR A325sc) from 45° (face surface) and 90° (lateral surface) viewpoints with 60 Hz frequency. At this stage of research, exact temperature was not determined, just the temperature distributions.

To understand the effect of the plastic sheet's presence on the heating process, three different setups were used: in the situation 'A', the steel pin was radiated directly at its face side, where the focal spot of the laser beam coincided with the steel pin surface. The diameter of the spot was Ø5mm in each case. In situation 'B', the PMMA plastic sheet was placed 0.5 mm above the steel pin, without touching it. In this case, because of the high transparency of the PMMA, about 92%, the laser beam passes the plastic and will be absorbed by the metal partner, where heat is generated (Kagan et al., 2003, Markovits et al., 2013). In situation 'C', the steel pin is pushed into the plastic sheet with a clamping force of 3.2 N during laser radiation. The heated face surface transfers heat back to the plastic, which softens and finally melts. As a result of the clamping force, the pin penetrates into the molten plastic and after cooling down a joint is created.

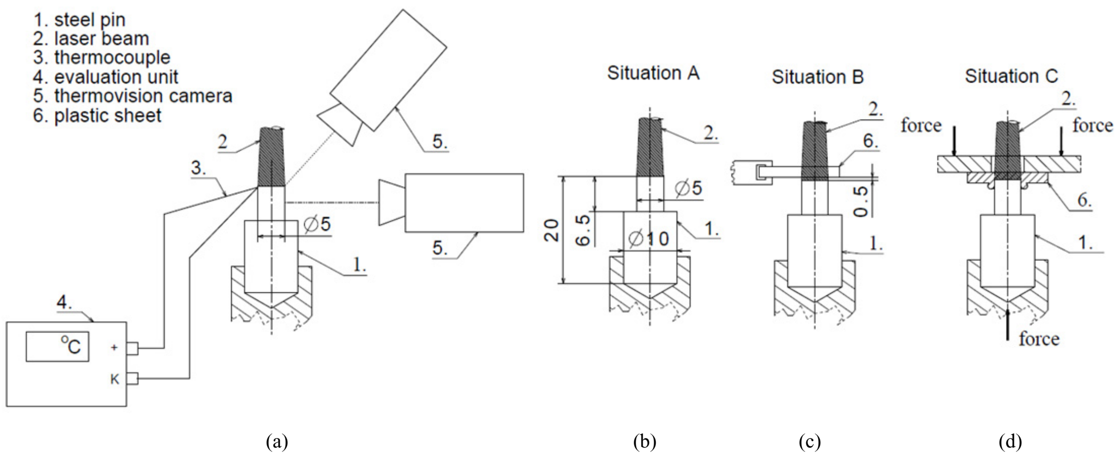



Fig. 1. (a) Schematic view of experimental setup in (b) Situation A; (c) Situation B; (d) Situation C.

In the experiments, three different laser settings were used, which are listed in Table 1. Each setting was used in all three situations, each experiment was repeated 3 times.

In each case 4.75 l/min argon shielding gas was applied and the average surface roughness of the steel pins on the lateral surface was altered between 0.8 µm and 1.5 µm. The pins were manufactured by turning. Roughness values were measured by a Mitutoyo Surftest 301 surface roughness tester. Before the experiment the steel pins were cleaned with acetone.

Table 1. Laser settings.

| | Pulse frequency (Hz) | Pulse time (ms) | Pulse energy (J) | Average power (W) | Irradiation time (s) |
|---|---|---|---|---|---|
| Setting I. | 100 | 0,5 | 2 | 200 | 4 |
| Setting II. | 5 | 9,9 | 40 | 200 | 4 |
| Setting III. | 100 | 0,5 | 2 | 200 | 7 |

To analyze the plastic side, the decomposition temperature was measured by conventional heating speeds 10 °C/min and 80 °C/min by a thermogravimetric (TGA) equipment.

## 3. Results

In Figure 2 the typical curves of the temperature measurements made by thermocouple are shown in situation A, in the case of the 3 different laser settings. The temperature reaches its maximum value at the end of the laser radiation, and after that, the temperature decreases to room temperature. As expected, the radiation time influences the maximal temperature strongly: in cases of setting I and III, the laser pulse properties are the same, only the radiation time differs; the longer heating causes higher temperature. However, as it can be seen at setting II, the different laser pulse mode influences the maximal temperature and the heating speed as well. Despite the fact that the radiation time is the same in setting I and II (4s), curve II has a higher heating speed, and reaches a higher maximal temperature value at the measured point (edge between lateral and face surface) as well.

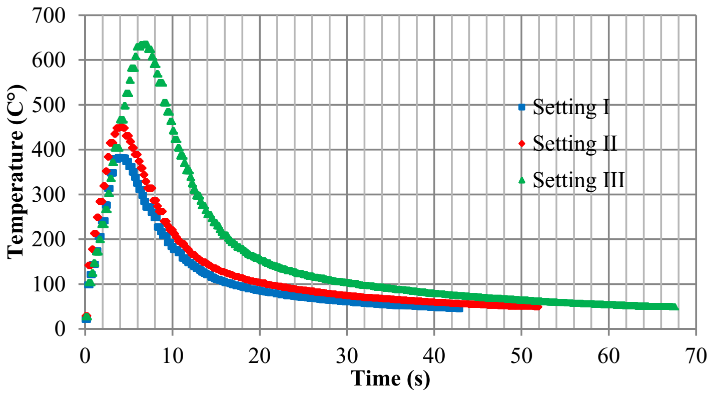



Fig. 2. Characteristic temperature curves in situation A at different laser settings, measured by thermocouple.

The measured maximum temperatures in the case of the three different laser settings are shown in Figure 3. In this diagram, the effect of the PMMA sheet can be observed on the maximum temperature which was reached at the top of the lateral surface of the pin. According to our latest results, the PMMA sheet placed above the steel pin in situation B decreases the temperature only slightly compared to situation A: the highly transparent PMMA sheet transmits the major part of the radiation, which interacts finally with the steel material. In situation C, when the steel pin penetrates into the plastic material, the maximum temperature is lowest among the 3 situations: the steel pin transmits heat to the PMMA, where the heat is used to heat up, melt and partly decompose the plastic material. The signs of the decomposition are the bubbles created close to the surface (shown in Figure 4c), which degrades the transparency of the plastic further, contributing to the lower temperature of the steel (Dakka, 2004).

If settings I and II are compared in case of situation C, it can be seen, that the temperature of the pin is lower when setting II is used, however, the temperature in situation A and B was about 50°C higher at setting II. The effect of radiation with low frequency and high pulse energy inside of the material is lower, because the material is not able conduct the heat fast enough to the regions deeper from the surface. Therefore the heat is accumulated and, due to the shorter pulse duration, the temperature will be higher for a short time. The accumulated heat next to the surface can be transferred easier to the environment, which leads to a lower temperature, when interacting with the plastic material.

In Figure 4 the different situations are illustrated at laser setting I, when the surface was just oxidized and not melted. In Figure 5 the face surfaces of the pins can be seen after heating in situation A. By using laser setting I, the surface is oxidized, in the case of setting II and III the surface is partly melted. This means, that specially at setting II, the surface reached the melting temperature of steel. In these cases, the PMMA placed above the steel in situation B also melted and started to decompose, which can be explained by the intensive thermal radiation of the metal. However, when the pin penetrates into the plastic, the steel does not melt: the plastic reduces the temperature of the steel, as mentioned before.

The above mentioned heat accumulation phenomena can be responsible for the melting of the face surface in the case of setting II at situation A and B as well. The melting of the surface also indicates that the temperature in the midpoint of the face surface reaches a higher value compared to the measured temperature at the edge.

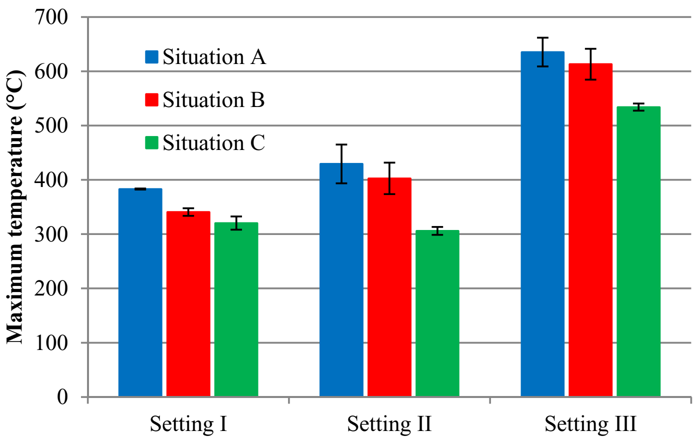
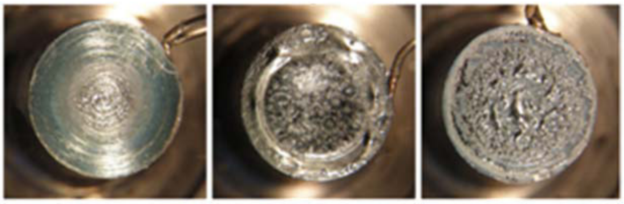



Fig. 3. The maximal temperatures at different laser settings and experimental situations.

(a) (b) (c)

Fig. 4. Face surface of the steel pins after different experimental situations at setting I: (a) Situation A; (b) Situation B; (c) Situation C.



(a) (b) (c)

Fig. 5. Face surface of the steel pins after different laser settings in situation A: (a) setting I; (b) setting II; (c) setting III.

As it is illustrated in Figure 4 c, the decomposition of the polymer material and bubble formation can be seen at the interface. This indicates a higher steel temperature, than the decomposition temperature of PMMA. Nevertheless, the decomposition process of the plastic is influenced by the heating speed: the higher heating speed shifts the peak of maximum weight change to higher temperatures, as shown in figure 6, where the TGA and DTGA curves of the PMMA material are plotted at heating rates of 10°C/min and 80°C/min. This means, that the temperature range at which the decomposition is the most intensive, is rising with the increasing heating speed. In the case of laser heating the heating speed is very high: 4500°C/min at least. This high heating speed can reduce the formation of bubbles and increase the temperature range of decomposition, and explain the less intensive bubble formation at higher temperatures.

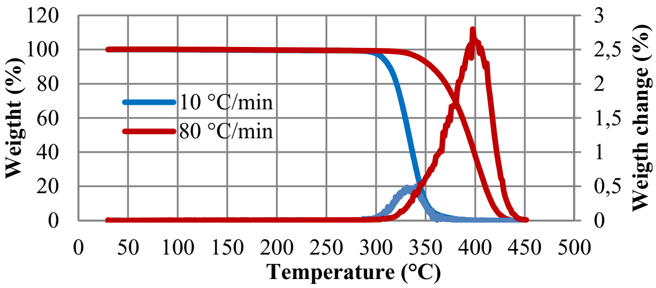



Fig. 6. Thermogravimetric curves of PMMA plastic.

The pictures of the infrared camera are able to visualize the heat distribution on the surface. In Figure 7 the heat distributions on the lateral surface of a pin in situation A at setting I are shown: the pictures 1 to 4 show the process of heating, in picture 4 the pin reaches its maximum temperature. In the 5$^{th}$ picture, the pin starts to cool down. In Figure 8 the horizontal temperature distributions of the lateral surface are plotted as a function of the distance from the face side.

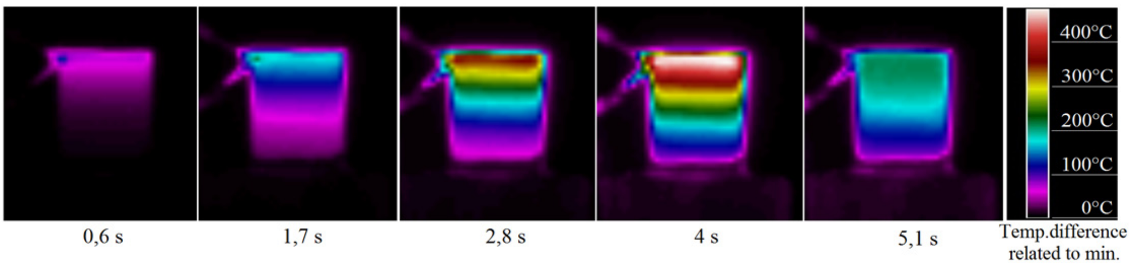



Fig. 7. Temperature time sequences on the lateral surface of the pin in setting I.

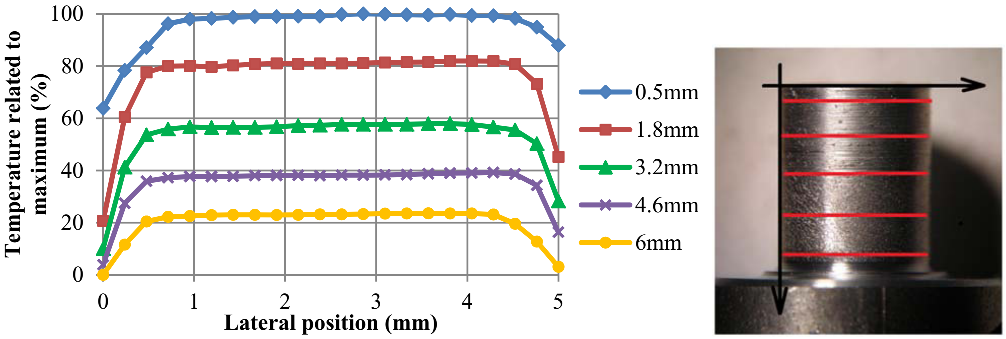



Fig. 8. Temperature distribution on the lateral surface of the pin in setting I as a function of vertical position.

From Figure 7 and 8 it can be seen, that the temperature on the lateral surface of the pin depends only on the time and on the vertical position. The temperature in horizontal position is uniform. (At the edges of lateral position the effect of cylindrical geometry on the infrared emission can be seen, which is the reason for decreasing values.)

In Figure 9, the heat distributions of the face surface in situation A at setting I are shown from a 45° viewpoint. In Figure 10 the horizontal temperature distributions of the face surface are plotted as a function of the time elapsed since the start of the irradiation. It can be seen, that the middle of the surface heats up faster, and the equalization of the temperature takes place partially only at the end of the process due to the Gaussian power distribution of the laser beam. Therefore, the PMMA material above the middle of the pin has to tolerate a higher temperature and that for a longer time, than the material close to the edge of the surface. This phenomenon explains the more intensive bubble formation in the middle of the plastic sheet, and the melting of the surface in some cases, which can be seen in Figure 4c and 5b.

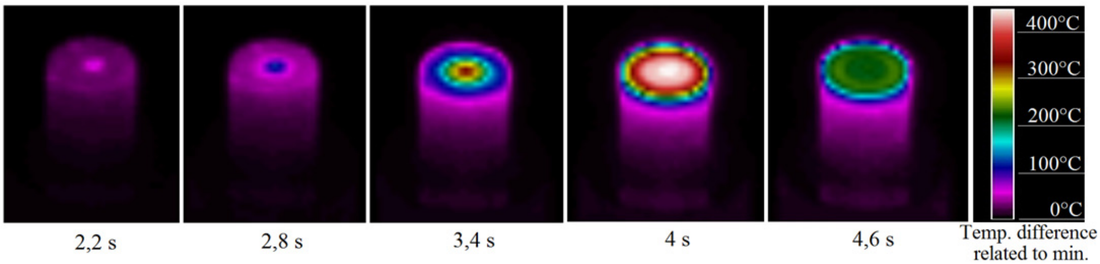



Fig. 9. Temperature time sequences on the face surface of the pin in setting I.

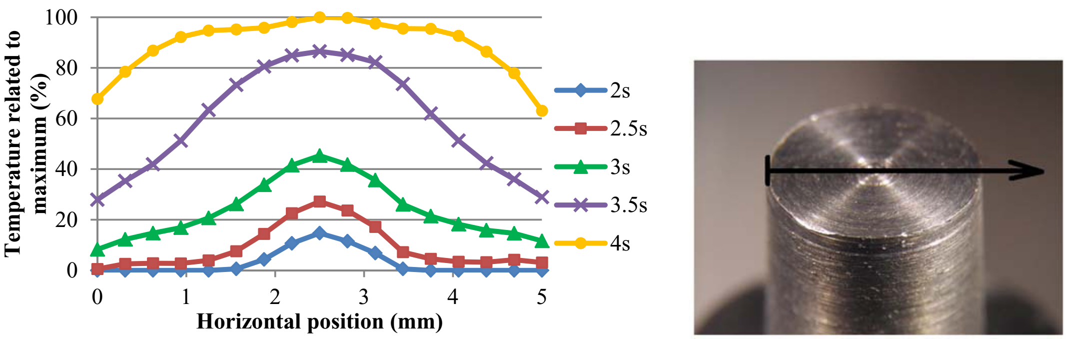



Fig. 10. Temperature distribution on the face surface of the pin in setting I as a function of radiation time.

Having determined the basic temperatures and temperature distributions in different cases, the next step is to determine exact temperatures on face surfaces. It can be derived from the results that the measuring process with the thermocouple is not fast enough to accurately detect the process and the position at the edge provide filtered information about the temperature on face surface. Objective of further research is to compare the exact temperature with the decomposition temperature of PMMA at real heating speed.

## 4. Conclusions

Summarizing the results of this work, the following conclusions can be drawn:

- The measurement method is able to provide basic information about the temperatures and their distributions in case of laser heating of steel pins
- The pulse mode of laser beam influences the speed of heating and cooling, and the maximum temperature present during the process as well: low frequency and high energy pulses increase the heating speed and the maximum temperature as compared to the high frequency and low energy pulses
- The PMMA material reduces the temperature of the steel pin. The temperature reduction is especially significant in the case of situation C
- The decomposition process of the polymer material depends on the heating rate: higher heating rates shift the temperature range of decomposition upwards; the heating speed is higher with an order of magnitude in case of laser heating than the one used in the TGA measurement
- The temperature distribution of the lateral surface of the pin is even and is the function of the distance from the face surface and time, and is independent from the horizontal position,
- In line with the Gaussian power distribution of the laser beam, the temperature distribution of the face surface of the pin shows a maximum value in the middle of the surface, which is responsible for the more intensive bubble formation in the PMMA material over the center of the joining.

## Acknowledgement

The authors want to express their thanks for the financial support to the Hungarian Scientific Research Fund (OTKA) (grant No. K 109436).

The authors are grateful for the support of Rhódium Ltd. providing during the temperature measurements.

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